DETERMINATION OF REMAINING STRENGTH OF CORRODED PIPELINE USING CLOSED – FORM SOLUTION

NUR FARIZA BINTI TALIB

Report submitted in partial fulfillment of the
requirements for the award of the degree of
Bachelor of Mechanical Engineering
Faculty of Mechanical Engineering

UNIVERSITI MALAYSIA PAHANG

18 JUNE 2013

ABSTRACT

Corrosion has become a main issue for all engineering sector in these decades. Failure due to corrosion has been one of the greatest concerns in maintaining the pipelines integrity. Therefore, corrosion defects must be accurately evaluated in order to avoid economic loss and environmental damages. It is very important to know the value of the maximum pressure which is critical application to considering in its design for safety and reability. The main purpose of this project is determine remaining strength of corroded pipeline using closed- form solution. New methods which is NEW UMP have been predict and applied compared with other method on difference literature that contain with difference material, gouge length, depth, outer diameter. The results obtained show that the NEW UMP has given the positive result for every criterion that has been test. NEW UMP also predict almost similar and closed with burst pressure value.

ABSTRAK

Pengaratan telah menjadi isu utama bagi semua sektor kejuruteraan dalam beberapa dekad. Kegagalan disebabkan oleh pengaratan telah menjadi salah satu kebimbangan yang paling besar dalam mengekalkan integriti saluran paip gas. Oleh itu, kecacatan karat mesti dinilai dengan tepat untuk mengelakkan kerugian ekonomi dan kerosakan alam sekitar. Ia adalah sangat penting untuk mengetahui nilai tekanan maksimum yang dalam reka bentuk untuk keselamatan. Tujuan utama projek ini adalah menentukan nilai tekanan maksima menggunakan kaedah lain. Kaedah baru iaitu UMP BARU telah diterbitkan dan bandingkan dengan kaedah lain iaitu yang mengandungi perbezaan dengan bahan, panjang kecacatan, dan diameter luar. Keputusan yang diperolehi menunjukkan bahawa UMP BARU telah memberikan hasil positif bagi setiap kriteria yang telah diuji. UMP BARU juga memberikan nilai yang hampir sama dengan nilai tekanan maksima.

TABLE OF CONTENTS

	Page
EXAMINER'S DECLARATION	ii
SUPERVISOR'S DECLARATION	iii
STUDENT'S DECLARATION	iv
DEDICATION	v
ACKNOWLEDGEMENTS	vi
ABSTRACT	vii
ABSTRAK	viii
TABLE OF CONTENTS	xi
LIST OF TABLES	xiv
LIST OF FIGURES	xvii
LIST OF ABBREVIATIONS	xviii

CHAPTER 1 INTRODUCTION

1.1	Introduction		1
1.2	Project Background		1
1.3	Project Objectives		2
1.5	Project Scopes		3

CHAPTER 2 LITERATURE REVIEW

2.1	Burst Test		4
	2.1.1	Classes of pipe Bursting	5
	2.1.2	Pipe Standard	8
2.2	Effect of pipe bursting on surrounding environment		10
	2.2.1	Ground Displacements	10
	2.2.2	Disposition of Pipe Fragments	11
	2.2.3	Ground Vibrations	12
	2.2.4	Effect on Nearby Utilities	13
	2.2.5	Positioning of the Replacement Pipe	14

2.3 Closed-Form Solution 16

2.3.1 Introduction 16
2.3.2 Method of the corrosion assessment 16
2.3.3 ASME B31G 18
2.3.4 MODIFIED ASME B31G 22
2.3.5 RSTRENG 24
2.3.6 PCORRC 26
2.3.7 DNV-RP-101 26
2.3.8 SHELL 92 28

2.4 Published of burst pressure 28

2.4.1 Finite element ductile failure simulation method using stress- modified fracture strain model 28
2.2.2 Ductile failure analysis of API X65 pipes with notch type defects using a local fracture criterion 34
2.2.3 Finite Element Analysis on Burst Pressure of Defective Steel Pipes 40
2.2.4 Model error assessments of burst capacity models for corroded pipelines 41
2.2.5 Effect of corrosion defects on burst pressure of pipeline 42
2.2.6 Failure assessments of corroded pipelines with axial defects using stress-based criteria. 43
2.2.7 Determination of burst pressure of API steel pipes using Stress Modified Critical Strain Model technique 48
2.2.8 Burst Pressure Prediction of Pressure Vessel using Finite Element Methods 50

CHAPTER 3 METHODOLOGY

3.0 Introduction 54
3.1 Flow Chart 55
3.2 Burst Pressure Test 56
3.3 Modified of Closed- Form Solution 57

3.3.1 New Equation 57

3.4 Burst Pressure Test Result 64

CHAPTER 4 RESULTS AND DISCUSSION

4.0 Introduction 68
4.1 Closed-Form Solution 68

4.2	New Equation	71
4.3	Comparison between difference materials	72
4.4	Comparison between difference outer diameter	76
4.5	Comparison between difference depth	81
4.6	Comparison between gouge length	83
4.7	Discussion	87

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

5.1	Conclusion	89
5.2	Recommendations	90

REFERENCE 91

APENDICES 94

Calculation of Closed-Form Solution

LIST OF TABLES

Table No.	Title	Page
2.1	Standard for aluminum tubes and pipe	9
2.2	History of methods	17
2.3	Basic statistic of model errors	21
2.4	Ranges of key parameters of applicable data for the burst models difference methods	22
2.5	Summarize of full-scale pipe tests	31
2.6	Chemical composition of the API X65 steel	35
2.7	Tensile properties of the API X65 steel	35
2.8	Summary of full-scale test of pipes with gouge defect	36
2.9	Chemical compositions and mechanical properties of the material	40
2.10	Mechanical properties of API X42 steel at room temperature	40
2.11	Summary of Burst Pressure Prediction of API X42 steel pipe	41
2.12	Geometric properties and burst pressures for the tested tubes	43
2.13	Mechanical properties of API X65 steel at room temperature	48
2.14	Result for finite element method	50
2.15	Result of half vessel with ends and without end caps	53
3.1	Comparison between Closed –form solution method using API X65	64
3.2	Comparison between Burst Pressure and Closed –form solution	64
3.3	Comparison between Closed –form solution method method using Diameter 508mm	64
3.4	Comparison between Closed –form solution method using Diameter 762mm	65
3.5	Comparison between Closed –form solution method using Diameter 1016mm	65
3.6	Comparison between Closed –form solution method using Diameter 41.94mm	65
3.7	Comparison between Closed –form solution method using	65

	Diameter 41.92mm	
3.8	Comparison between Closed –form solution method using API X52	66
3.9	Comparison between Closed –form solution method using API X65	66
3.10	Comparison between Burst Pressure and Closed –form solution	66
3.11	Comparison between Burst Pressure and Closed –form solution	66
4.1	Comparison between Burst Pressure and Closed –form solution	69
4.2	Comparison between Closed –form solution method and new equation method using API X65	72
4.3	Comparison between Closed –form solution method and new equation method using API X52	73
4.4	Comparison between Closed –form solution method and new equation method using API X42	73
4.5	Comparison between Closed –form solution method and new equation method using Diameter 508mm	76
4.6	Comparison between Closed –form solution method and new equation method using Diameter 762mm	76
4.7	Comparison between Closed –form solution method and new equation method using Diameter 1016mm	77
4.8	Comparison between Closed –form solution method and new equation method using Diameter 41.94mm	77
4.9	Comparison between Closed –form solution method and new equation method using Diameter 41.92mm	77
4.10	Comparison between Burst Pressure and Closed –form solution method	81
4.11	Comparison between Burst Pressure and Closed –form solution	84
4.12	Comparison between Burst Pressure and Closed –form solution	84

LIST OF FIGURES

Figure No.	Title	Page
2.1	Comparison of smooth and notched bar tensile test results with simulated (a) notch radius = 1.5 mm, (b) notch radius = 3 mm, (c) notch radius = 6 mm, and (d) smooth bar.	29
2.2	(a) FE pressure–displacement curves including predicted failure points, and (b) comparison of predicted burst pressures with experimental ones.	31
2.3	(a) Stress triaxiality distributions and (b) equivalent strain distributions for smooth and notched tensile bars at the failure initiation point, determined from the FE analyses.	33
2.4	(a) Variations of the stress triaxiality with the equivalent strain for smooth and notched bar tensile tests, and (b) fracture strain as a function of the stress triaxiality.	34
2.5	Comparison of smooth and notched bar tensile test with simulate Finite Element	39
2.6	3-D finite element model for the API X65 pipe specimen with 900mm defect tested by Kim	45
2.7	Mises stress contours with increased internal pressure for the deep flaw (a/t = 0.5) pipe with groove-shaped defect and n = 10.	46
2.8	Mises stress contours with increased internal pressure for the shallow flaw (a/t = 0.2) pipe with groove-shaped defect and n = 10.	47
2.9	FEA of Half Vessel with end caps	51
2.10	FEA of Half Vessel without end caps	52
3.1	The Process Flow Chart	55
3.2	Graph of pressure percentage against defect length of API X65 with d/t = 0.5	61
3.3	Graph of pressure percentage against defect length of API X65 with d/t = 0.25	61
3.4	Graph of pressure percentage against defect length of API X65 with d/t = 0.75	62

4.1	Graph of pressure percentage against defect length of API X65 with d/t = 0.5	69
4.2	Graph of pressure percentage against defect length of API X65 with d/t = 0.25 and 0.75	70
4.3	Graph of pressure percentage against defect length of APIX65 with d/t = 0.5	74
4.4	Graph of pressure percentage against defect length of API X52 with Do = 41.95	74
4.5	Graph of pressure percentage against defect length of API X42 with $d/t = 0.25$.	75
4.6	Graph of pressure percentage against defect length of API X42 with Do = 508mm	78
4.7	Graph of pressure percentage against defect length of API X42 with Do = 762mm	79
4.8	Graph of pressure percentage against defect length of API X42 with Do = 1016mm	30
4.9	Graph of pressure percentage against defect length of API X42 with Do = 41.94mm	80
4.10	Graph of pressure percentage against defect length of API X42 with Do = 41.92mm	80
4.11	Graph of pressure percentage against defect length of API X65 with d/t = 0.5	82
4.12	Graph of pressure percentage against defect length of API X65 with d/t = 0.25	83
4.13	Graph of pressure percentage against defect length of API X65 with d/t = 0.75	83
4.14	Graph of pressure percentage against defect length of API X65 with l = 100mm to 600mm	86
4.15	Graph of pressure percentage against defect length of API X65 with l = 100mm to 200mm	86
4.16	Graph of pressure percentage against defect length of API X65 with l = 50mm to 900mm	87

LIST OF ABBREVIATIONS

AISI	American Iron and Steel Institute
ASTM	American Society for Testing and Materials
ANSI	American National Standards Institute
AFNOR	Association Francoise de Normalisation
ASME	American Society of Mechanical Engineers
BSI	British Standards Institution
ISO	International Organization for Standardization

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Failure due to corrosion have been one of the greatest concern in maintaining the pipelines integrity. Therefore, corrosion defects must be accurately evaluated in order to avoid economic loss and environmental damages. Its is very important to know the value of the maximum pressure which is critical aplication to considerion in its design for safety and reability.The determination of corroded pipes load capacity is an important topic for research. There are several emprical and semi- emprical methods available to determine the load capacity of corroded pipelines based on experimental test. Besides that, these methods are known to be conservative and limited since they are dependent on material properties, pipelines geometries and defect geometry.

1.2 PROJECT BACKGROUND

Most people associate pipes with the hot and cold water they see in their houses. Also, most of us will have seen the plastic pipes laid under our streets and roads to locally distribute natural gas. But what many people do not know is that there are hundreds of thousands of kilometres of very large pipelines crossing our nations and oceans delivering and transmitting huge quantities of crude oil, oil products, and gas. Most are underground or undersea.

Crude oil is often transported between continents in large tankers, but oil and natural gas is transported across continents by pipelines. These pipelines are very large diameter (the Russian system has diameters up to 1422mm), and can be over 1000 km in length. For example in the USA, the vast pipeline oil and gas pipeline system consist of Onshore Gas Transmission 295,000 miles (472,000km), Offshore Gas Transmission 6,000 miles (10,000km), Onshore Gas Gathering 21,000 miles (34,000km), Offshore Gas Gathering 6,000 miles (10,000km), Liquid Transmission Lines 157,000 miles (251,000km). This list ignores the 1,000,000 miles (1,600,000km) of low pressure gas distribution pipelines in the USA, and pipelines carrying water, sewerage and slurries.

Pipeline has been widely used for transporting oil, gas and other liquid in petroleum, chemical and other energy industries. During installation, the pipelines are often subjected to third party accident in which cause gouge and dent defect on the surface. All incident and mileage data for the period from January 2008 through July 2012 (10.58 years of data) are sufficient for use and are most applicable to these estimates. The Consequences Summary Statistics for overall industries perspective, from 2008 until 2012 shows that in percentage of public facilities, industries facilities, public injuries and industries injuries are increase from year to year which is for public facilities increase 63% to 90%, industries facilities increase 10% to 36%, public injuries increase 67% to 76% and industries injuries increase 23% to 32%. Besides that after a few years, the pipeline is subjected to corrosion. In this project, the method of corrosion assessment will be applied in order to reduce failure and damage part of the pipeline.

1.3 PROJECT OBJECTIVE

The objective of conducting this project is to develope new Closed- form Solution to determine the burst pressure of corroded pipeline from available pipeline design code that will improve the value of burst pressure.

1.4 SCOPE OF THE PROJECT

The scope of carrying out this project includes:

i. Literature riview and collecting data of burst pressure from published literature.

ii. Determine the method of corrosion assesment with difference gouge length

iii. Result with difference closed- form solution will be compared.

iv. Improvement of Closed- form Solution.

CHAPTER 2

LITERATURE REVIEW

2.1 BURST TEST

Prediction of the bursting pressure used in a critical application that is an important consideration in design for a safety and reliability. It is very important to know the value of maximum pressure (Rajan, 2007). The test is to determine at the point when the ligament failed. From the test we can determine at the point when ligament failed (Chang, 2011). Test result shows that burst pressure decreases with increase gouge length. All specimens show bulging deformation around defect area and occurred at the bottom of the defect area with crack. The result pressure value and decrease with increase radial displacement.

Burst Test is a well-established method for trenchless replacement of pipe throughout the world. Pipe bursting was first developed in the UK in the late 1970s by D. J. Ryan & Sons (Howell, 1995) in conjunction with British Gas, for the replacement of small-diameter, 3 and 4-inch cast iron gas mains. This method was patented in the UK in 1981 and in the United States in 1986, these patents expired in April 2005. Since the late 1970s pipe bursting has grown into a mature market internationally with significant potential for continued growth in the oil and gas, water supply and sewer. The National Association of Sewer Service Companies (NASSCO) was established in 1976 and is the oldest such association with a trenchless focus. The IPBA (International Pipe Bursting Association) was founded in 2000 as a division of NASSCO with the purpose of developing standards for the use of pipe bursting in the sewer market in the United States. A re-organization of the association in 2010 brought together professionals from all aspects of the pipe bursting industry who developed a strategic plan to collaboratively promote pipe bursting throughout sewer, water, gas, and other underground utility market.

Besides, Burst Test is a method for replacement of undersized gas, water and sewer pipes. An existing pipe is replaced size-for-size or up-sized with a new pipe in the same location. The technique is the most cost effective when there are few lateral connections, when the when additional capacity is needed. Burst Test, which can be either pneumatic, hydraulic expansion or static pull, fractures a pipe and displaces the fragments outwards while a new pipe is drawn in to replace the old pipe.

In addition to pipe bursting there are several other methods for trenchless pipe replacement, which differ in the way the old pipe is fractured and the fragments displaced. Pipe implosion fractures the pipe inwards prior to the outward displacement of the pipe fragments. Pipe splitting splits open existing ductile pipes. Specially designed variations of the micro tunnelling system and of the reaming process from horizontal directional drilling are used in pipe eating and pipe reaming to excavate the old pipe in fragments. Both methods remove the fragments to the surface through circulating slurry rather than displacing them. Pipe ejection jacks out the old pipe towards a receiving pit (manhole) where it is broken up and removed while the new pipe is being inserted.

2.1.1 Classes of Pipe Bursting

Pipe bursting systems are primarily classified into two classes which are pneumatic pipe bursting and static pipe bursting, which is based on the type of bursting tool used. The basic difference among these systems is in the source of energy and the method of breaking the old pipe and some consequent differences in operation. The selection of a specific replacement method depends on geotechnical conditions, degree of upsizing required, the type of new pipe, construction of the existing pipeline, depth and profile of the existing pipeline, availability of experienced contractors and equipment, risk assessment, and other possible site specific issues.

For Pneumatic Pipe Bursting, the bursting tool is a soil displacement hammer driven by compressed air. An expander is fitted to either the front or near the rear of the pneumatic soil displacement hammer. The pneumatic hammer assembly is launched into the host pipe via an insertion pit. The tool is connected to a constant tension winch located at the receiving point. The constant tension of the winch keeps the tool and expander in contact with the unbroken section of pipe and centered within the host pipe and when combined with the percussive power of the hammer helps maintain the hammer and expander inside the existing pipe. The percussive action of the hammering cone-shaped head is similar to hammering a nail into the wall; each hammer stroke pushes the nail a short distance. It cracks and breaks the existing pipe, with each stroke.

The expander combined with the percussive action push the fragments and the surrounding soil away providing space for the new pipe. Reversible tools are available that allow the pneumatic hammer to back itself out through the installed pipe saving the expense of a reception pit (Sterling, 2001). Once started, the burst continues to the destination manhole/reception pit where the tool/expander assembly is retrieved. The process continues with little operator intervention until the head reaches the pulling shaft at which point it is separated from the new pipe. In regards to pneumatic pipe bursting operations considerations should be made for the noise generated by the air compressor and pneumatic hammer. Generally the noise is concentrated near the open end of the replacement pipe due to the release of pressure associated with the pneumatic action through the new pipe.

For Static Pipe Bursting, no hammering action is used, as a large pull force is applied to the cone-shaped expansion head through a pulling rod assembly or cable inserted through the existing pipe. The cone transfers the horizontal pulling force into a radial force - breaking the existing pipe and expanding the cavity providing space for the new pipe. With the rod method steel rods are inserted into the existing pipe from the pulling shaft. The rods are connected together using different types of connections. When the rods reach the insertion shaft, the bursting head is connected to the rods and the new pipe is connected to the rear of the head. A hydraulic unit in the pulling shaft pulls the rods one rod at a time, and the rod sections are removed. The bursting head and the new pipe are pulled with the rod or the cable fracturing the existing pipe and pushing the debris to the surrounding soil.

In the hydraulic expansion system, the bursting process advances from the insertion pit to the reception (pulling) pit in sequences, which are repeated until the full length of the existing pipe is replaced. In each sequence, one segment of the pipe is burst in two steps: first the bursting head is pulled into the old pipe for the length of the segment, and then the head is expanded laterally to break the pipe (Tucker, 1987). The bursting head is pulled forward with a winch cable, which is inserted through the old pipe from the reception pit, and attached to the front of the bursting head. The rear of the bursting head is connected to the replacement pipe and also the hydraulic supply lines are inserted through the replacement pipe. The bursting head consists of four or more interlocking segments, which are hinged at the ends and at the middle. An axially mounted hydraulic piston drives the lateral expansion and contraction of the head.

The process continues until the bursting head reaches the pulling shaft, where it is separated from the new pipe. If a cable or winch is used instead of a rod assembly, the pulling process continues with minimum interruption, but the force available for the operation is less. Roller blade cutting wheel assemblies allow bursting of non-fracturing types of pipe such as steel and ductile iron water pipes and ductile iron repair clamps. Due to the use of a bursting head or a roller blade cutting wheel assembly, static pipe bursting systems can burst both factorable and non-factorable host pipe materials (Semisevic, 2000). Static pipe bursting technology encompasses the "pipe splitting" method which is essentially the addition of a "splitter" or "slitter" in front of the pipe burst expander head that splits the existing pipe.

The operation and equipment is the winch and pulling cables are used to pull the bursting tool through the pipe, the winch is placed into an existing manhole structure or a reception pit, and the cable pulled through the pipe and attached to the front of the bursting unit in an insertion pit. The winch helps to ensure the directional stability in keeping the unit on the line of the existing pipe. The winch must supply sufficient cable in one continuous length so that the pull may be continuous between winching points.

The winch, cable and cable drum must be provided with safety cage and supports so that it may be operated safely without injury to persons or property. When rigid pulling rods are used instead, they are inserted from the reception pit through the existing pipe until the pipe insertion point is reached. The rods are then attached to the bursting head, and pulled through the existing pipe

2.1.2 Pipe Standard

The integrity of a piping system depends on the considerations and principles used in design, construction and maintenance of the system. Piping systems are made of many components as pipes, flanges, supports, gaskets, bolts, valves, strainers, flexible and expansion joints. The components can be made in a variety of materials, in different types and sizes and may be manufactured to common national standards or according a manufacturers proprietary item. Some companies even publish their own internal piping standards based upon national and industry sector standards. Piping codes and standards from standardization organizations as ANSI, ASME, ISO, DIN and others, are the most common used in pipes and piping systems specifications. Piping standards define application design and construction rules and requirements for piping components as flanges, elbows, tees, and valve. A standard has a limited scope defined by the standard.

ASTM International, known until 2001 as the American Society for Testing and Materials (ASTM), is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services. The organization's headquarters is in West Conshohocken, Pennsylvania, about 5 miles (8 *km*) northwest of Philadelphia. ASTM, founded in 1898 as the American Section of the International Association for Testing and Materials, predates other standards organizations such as BSI (1901), DIN (1917), ANSI (1918) and AFNOR (1926). ASTM has a dominant role among standards developers in the USA, and claims to be the world's largest developer of standards. Using a consensus process, ASTM supports thousands of volunteer technical committees, which draw their members from around the world and collectively develop and maintain more than 12,000 standards. For Aluminium pipe mostly used ASTM B210 as the guide. Table 2.1 shows the standard for aluminium tubes and pipes.

Table 2.1: Standard for aluminum tubes and pipe

Types	Description
ASTM-B-210	Drawn Seamless Aluminum Alloy Tubes for General Purpose & Pressure Applications.
ASTM-B-221	Extruded Aluminum Alloy Tubes for General Purpose Applications.
ASTM-B-234	Drawn Seamless Aluminum Alloy Tubes for Condensers & Heat Exchangers.
ASTM-B-235	Aluminum Alloy Extruded Tubes.
ASTM-B-241	Seamless Extruded Aluminum Alloy Pipe & Tube for General Purpose & Pressure Applications.
ASTM-B-313	Aluminum Alloy Round Welded Tubes.
ASTM-B-317	Extruded Aluminum Alloy Pipe for Electrical Bus Conductors.
ASTM-B-345	Seamless Extruded Aluminum Alloy Tubes & Pipe for Gas & Oil Transmission and Distribution Piping Systems.
ASTM-B-404	Seamless Aluminum Alloy Condenser & Heat Exchanger Tubes with Integral Fins.
ASTM-B-429	Extruded Aluminum Alloy Structural Pipe & Tube.
ASTM-B-483	Drawn Aluminum Alloy Tubes for General Purpose Applications.
ASTM-B-491	Extruded Round Coiled Aluminum Alloy Tubes for General Purpose Applications.
ASTM-B-547	Aluminum Alloy Formed and Arc Welded Round Tube.

2.2 EFFECT OF PIPE BURSTING ON SURROUNDING ENVIRONMENT

2.2.1 Ground Displacements

Every bursting procedure is associated with ground displacements. Even when the replacement is carried out size-for-size, soil movements are created because the bursting head has a larger diameter than the replacement pipe. Ground movements are not exclusive to pipe bursting, and they can be significant in open trench replacements of pipes as well (Rogers, 1995). The general explains behavior of the ground movements under particular site conditions, in what conditions can be of concern, and suggests some minimal requirements for pipe bursting operations. The direction of the least soil resistance is expanding of the soil displacements from the source through the soil which is function of time and space. During over time after the burst the displacements are the greatest during the bursting operation.

In relatively loose soils and for small diameter pipes, a uniform expansion is expected at a depth of 2 *ft*, whereas in relatively dense soils the expansion at this depth would still be predominately upwards (Chapman, 1996). If the ground movements are not attenuated before reaching the surface, they cause either surface heave or settlement. The ground movements generally tend to spread symmetrically around the vertical axis through the existing pipe, and heave or settlement is usually expected directly above the pipe. The ground displacements depend primarily on degree of upsizing, type and compaction level of the existing soil around the pipe, and depth of bursting. In a relatively homogeneous soil with no close rigid boundaries, the displacements are likely to be directed upwards at smaller depths, while at increased depths they are expected to have more uniform direction. They generally tend to be localized, and to dissipate rapidly with the distance from the source.

If the existing soil is loose sand or relatively new trench backfill which is still settling, the bursting process can act to further settle the existing soil. The diameter increase is compensated by soil compaction within a short distance of the pipe, and outside of that zone settlement may occur. This is the case when the pipe is upsized in a loose soil that will be compacted by ground vibrations. Proximity of a rigid boundary may break the vertical symmetry and shift the surface heave to the side. It is a combination of many factors that determines whether the surface will heave or settle. Also, surface heave and settlement may sometimes both be present. Otherwise, if the soil is well compacted and the pipe not very deep, the bursting process is likely to create a surface heave, especially when significantly upsizing the existing pipe.

The most critical conditions for the occurrence of considerable ground displacements (Atalah, 1998) are when the existing pipe is not deep and the ground displacements are directed upwards already large diameter pipes are significantly upsized, there are deteriorated existing utilities within 2-3 diameters of the existing pipe. In sands, the tail void (annular space) created by the bursting head can easily collapse locally. The soil displacement profiles tend to be more predictable in cohesive soils. The ground displacements should be acceptable if the bursting is performed under a certain minimum depth of cover and at certain distance from adjacent buried utilities.

2.2.2 Disposition of Pipe Fragments

The size and shape of the fragments of the existing pipe, and their location and orientation in the soil during and after the bursting process, are of interest with respect to the potential damage to the replacement pipe. The pipe fragments generally tend to settle at the sides and bottom of the replacement pipe in sand backfill, or locate all around the perimeter of the replacement pipe in silt or clay backfill .The damage to the pipe can occur either during the bursting process, or later during soil settlement, especially if assisted by external loading. In a limited study of pipe fragments following busting carried out at the TTC test site, two different patterns in which the fragments settle in the soil (Atalah, 1998) were distinguished depending on the soil type.

In a study of this issue, the greatest threat to the replacement pipe was found to be the small pipe fragments with a 20-degree tip, and oriented at 90 degrees to the top of the new pipe, but the probability of actual perforation was found to be rather low .If the replacement pipe gets only scratched in the bursting process, the problem is generally not serious for applications with no or low internal pressure, especially if the scratches are not deep. In addition, the scratching of the replacement pipe can be offset by choosing a higher than minimum pipe wall thickness (Standard Diamater Ratio - SDR). The fragments tend to locate somewhat away from the replacement pipe, with a typical separation up to 1/4 inch. This indicates a "soil flow" during the bursting process: the bursting head with its diameter larger than the replacement pipe creates the annular space, which is subsequently filled with the soil. Orientation of pipe fragments is important when establishing the risk of new pipe perforation by the fragments (Wayman, 1995). For pressure pipe applications, a sleeve pipe is typically installed during the bursting operation with the product pipe installed later within the sleeve.

2.2.3 Ground Vibrations

The study showed that none of the pipe bursting techniques tested is likely to damage the nearby utilities if they are at a distance of more than a few feet from the bursting head. The vibration levels due to bursting depend on the power (impact) applied through the bursting process, and therefore on the size and type of the existing pipe, and the degree of upsizing. An extensive study of the velocity of vibration ground movement was done by the TTC for three different pipe replacement techniques: pneumatic pipe bursting, hydraulic expansion, and static pull. All pipe bursting operations create to some extent vibrations of soil particles in the ground. The study covered a variety of job site conditions through several job sites in various regions of the U. S. and the TTC Test Site in Ruston, Louisiana.

In addition, buried pipes and structures are able to withstand much higher levels of vibration than the surface structures of similar integrity, and the vibrations are even less expected to cause distress to buried structures. The vibrations caused by pipe bursting tend to have a frequency that is well above the natural frequency of buildings. The maximum velocity of soil particles ordinarily does not exceed the threshold criteria for cosmetic cracks in buildings, developed by the U. S. The values measured in the TTC study were in the range between 30 and 100 Hz, whereas the natural frequency of buildings is typically in a range from 5 to 11 Hz. Bureau of Mines and the Office of

Surface Mining, for associated frequencies of ground vibrations. The vibration levels due to bursting depend on the power (impact) applied through the bursting process, and therefore on the size and type of the existing pipe, and the degree of upsizing.

The vibrations caused by pipe bursting tend to have a frequency that is well above the natural frequency of buildings. The vibrations caused by pipe bursting were also found to be unlikely to cause cracks in nearby buildings. The maximum velocity of soil particles ordinarily does not exceed the threshold criteria for cosmetic cracks in buildings, developed by the U. S. The values measured in the TTC study were in the range between 30 and 100 Hz, whereas the natural frequency of buildings is typically in a range from 5 to 11 Hz. Bureau of Mines and the Office of Surface Mining, for associated frequencies of ground vibrations. In addition, buried pipes and structures are able to withstand much higher levels of vibration than the surface structures of similar integrity, and the vibrations are even less expected to cause distress to buried structures.

2.2.4 Effect on Nearby Utilities

The use of a sleeve in the pipe bursting intensifies the radial expansion of loading through the soil, and potentially increases risk of damage to the adjacent pipes. The response of the adjacent pipe to the disturbance from the bursting operation depends on the position of the pipe relative to the direction of bursting (Wayman, 1995). Ground movements during the pipe bursting operation may damage nearby pipes or structures. A parallel adjacent pipe is subject to transitory disturbance, as the bursting operation is progressing. If the adjacent pipe is diagonally crossing the line of bursting, it undergoes longitudinal bending as it is pushed away from the bursting line. The severity of disturbance on the adjacent pipe depends on the type of soil. If the pipes are located in the weak soil (backfill which has not been well compacted and is still below the level of compaction of the surrounding ground), the load transfer is less significant than through a strong, incompressible soil. Mechanical joints on pipes can easily leak, when disturbed by ground movements. Brittle pipes are the most susceptible to serious damage.